Mono-digesters on laying hen manure in Jordan
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Introduction

All-renewable energy resources are required to reduce dependency on fossil fuels from politically unstable regions. Manure and straw form combined a good substrate to produce biogas, but straw is in most areas used for other purposes and there it is not economically to use straw as substrate (Oosterkamp 2014). In Jordan and Indonesia I visited egg farms with the request to assess the possibility of producing biogas with mono-digesters based on hen manure. In both countries straw was not available. Jordan faces the extra difficulty of lack of water and lack of mineral oil.

The operation of digesters on chicken manure alone is generally very problematic due to the high nitrogen content of the manure. The most common application method is the dilution of manure with water or co-digestion with other available organic substances. Both alternatives have their inherent disadvantages. The dilution method requires a significant amount of water, which is not available in arid regions. The effluent of the digester has then to be processed in order to be used as irrigation water. Co-substrates are not available in Jordan and in some places in Indonesia.

This note explores the available information on digestion of hen manure and makes a proposal for a biogas plant using a mono-digester.

Operating hen manure only digesters (mono-digesters)

Safley et al. (1987) describe a biogas plant at the North Carolina State University, that was operated for three years. Other biogas plants operating on pure chicken manure are located in China (2 000 kW_e manure of three million layer hens)(Wang, F. 2011), Bangladesh (300 Kw_e poultry waste; Saha, S. 2012) and in Ohio United States (one million layer hens). Gas yield of the Chinese plant is similar to that of Safely et al. (1987).The volume of the digesters per hen is only half of that of Safley et al. (1987) suggesting a shorter retention time and higher solids loading for the Chinese digesters.

Available experiments with pure laying hen manure

Tests on biogas production (continuously fed digesters) from laying hen manure have been reported by Webb et al. (1985), Safley et al. (1987) and Preeti Rao et al. (1994). Their data are summarized in table I.

Table I Tests on biogas from laying hen manure.

	Webb et al. 1985	Webb et al. 1985	Safley et al. 1987	Preeti Rao et al. 1994
Temperature	35	35	35	37
Retention time days	15	15	22	10
Influent total solids	0.100	0.060	0.059	0.075
Influent volatile solids	0.068	0.041	0.039	0.039
Influent total N g/l	5.5	3.3	5.5	4.4
Effluent ammonia concentration mg/l	0.14	0.29	n.a.	n.a.
Methane yield l/kg VS	230	240	225	260

The gas yield of Preeti Rao et al. (1994) is high as 10% of well acclimated digester effluent (sludge) was added to the input. Webb et al. (1985) performed test of laying hen manure with an average age of 3.5 days. It is assumed that the manure in the other experiments is fresh, as no details are given.

Gas yields of Webb et al. (1985) at a retention time of 30 days are similar to those at 15 days. The free ammonia levels are 50 % to 100 % higher at the longer retention times, due to the conversion of urea to ammonia and the degradation of proteins. This indicates that higher total solids loading are possible provided the retention time is short.

Tao et al. (2008), Webb et al. (1985), Preeti Rao et al. 1994 have a value of total nitrogen of 5 - 7 g/kg total solids. Safley et al. (1985), Kougias (2013) and Gelegenis et al (2007) have values that are around 9 - 11 g/kg total solids.

The free ammonia concentration (which is the limiting factor in the anaerobic digestion of hen manure) from the test by Webb et al. (1985) can be expressed by:

$C = C_0 * x^{1.5} * t^{.05}$ eq. 1

- x is the total nitrogen in g/l
- t is the digestion time.
- C_0 is 5.8

We obtain a free ammonia concentration of 352 mg/l using the data of Safley et al. (1987) and equation 1. The methane production at 225 l/kg VS is not inhibited. The pH (8.0) is similar (7.8) to that of Webb at 15 days retention time and a loading of .1 kg/l of TS. It seems that a higher total loading, than that used by Safley et al. (1985) is possible.

Kougias et al. 2013 performed batch digestion tests on hen manure and hen manure with a natural zeolite added. The test without zeolite (with digested swine manure as inoculum) was inhibited. Free ammonia is reduced at the low pH.

Table II

	Kougias			Safley
Zeolite concentration	10 g/l	5 g/l	0 g/l	0 g/l
Total nitrogen	5.5 g/l	5.5 g/l	5.5 g/l	5.5
Methane yield	270 l/kg	230 l/kg	120 l/kg	225 l/kg
Free Ammaonia	0.24 g/l	0.25	0.27	
pH	7.9	7.8	7.1	8.0
volatile fatty acids	1.1 mg/l	3.3 mg/l	10.1	3.4 mg/l

There is a good correlation between pH and gas yield and the inverse of the volatile fatty acids.

Preeti Rao et al. (1994) report that the methane yield is increased to 390 l/kg VS (plus 40 %), when 20 mN (1 g/l Fe2+) of FeSO4 is added to the input. Volatile solids reduction, in that case, is 75 %. The iron dose is much higher than required for the removal of H_2S and it is likely that the iron acts as a flocculation agent. The number of methanogenic cells increased by three orders of magnitude. The reduction in volatile fatty acids is less than 10 %. The growth of methanogenic cells reduces the free fatty acids and immobilizes some of the ammonia.

Zhang et al. 2012 performed batch tests on the effect of addition of 0.5 g/l Fe^{2+} to the substrate (TS 7.7 %) and observed an increase in methane yield at 20 days retention of 35 %.

Design considerations

Solids concentration

The maximum solid concentration is limited by the free ammonia concentration in the digester. In order to calculate the maximum total solids concentration of hen manure we use the following assumptions:

- A ratio of total nitrogen to total solids of 0.09 Safely et al. (1987).
- A maximum free ammonium concentration of 435 mg/l (Webb et al. 1985).

The maximum allowable total solids concentration is then 9 %, with a digestion time of 10 days. This is consistent with Safley et al. (1987).

Build-up of grit inside the digester tank will take place at a total solids concentration of 9%. Digesters with 14 % of solids do not show any accumulation of solids in the digester (Hills et al. 1984).

Low nitrogen materials like waste from olive oil processing (liquid and solid) or wood chips from olive pruning and olive trees are preferred to increase the solids loading. Also sludge from the waste water clean-up of a paper factory is a possibility. These materials make the biogas plant dependent on outside sources, which may not be prudent.

The loading of hen manure can be increased to a solids content of 10 %, when 4 % of a natural zeolite is added. A total solid fraction of 14 % is reached.

There are different natural zeolites in Jordan (Al-Dwairi 2013 and Saradqah 2010). Estimated costs is about 50 €/ton at the poultry farm. Costs in Europe are between 100 and 150 €/ton depending on packaging.

It makes sense to add iron-hydroxide, which is a waste product from the production of drinking water. Around 1.2 g/l of Fe^{++} in the form of FeOH can be added, based on the data of Preeti Rao et al. (1994).

The 1 % TS hen manure and 2 % of the zeolite and all the water can be substituted by olive mill effluent, during the olive processing season, thus reducing the costs for the zeolite. It is estimated that the olive mill effluent can be obtained at little or no costs from nearby olive mills. Methane yield will be increased with 25 %. The generator must then be sized for this extra load.

Gas yield

The volatile solids loading of the plant is 9 ton per day, based on a volatile solids production of 0.018 kg VS per hen and day (Safley et al. 1985) and 500 000 hens. Tao et al. 2008 give a value of 0.022 kg per hen and day. Safley et al. (1987) and Wang (2011) give a *biogas* production per hen and day of 0.07 m^3/d with 60 % methane. Safley et al. 1987 have measured a methane yield of 225l/kg VS, which is consistent with a value of 0.004 m^3/(hen.day).

The second digester tank generates an extra 15 % gas (Angelidaki et al. 2005) and the use of $Fe(OH)_3$ in the digestion tank will increase the biogas yield with a conservative estimate of 20 %. Total methane yield is 0.006 m^3/d per hen or 3 000 m^3/d for the farm.

Design of a 550 kW_e biogas plant with hen manure as substrate

Substrate preparation

Manure from the hen houses is transported by conveyor bands into a ten tons dump truck. This dump truck unloads into a sub surface mixing tank of 4 m diameter and 4 m height. This chamber is filled with 16 m3 hot water with a temperature of 60 o C. Mixing is done by a Stamo top mounted mixer. The mixture temperature is 42 o C. Hot water is produced by a boiler heated from the cooling circuit of the generator engine. An electric heater is provided for start-up purposes.

Table II Substrate composition

Substrate	input tons	total solids	volatile solids
Laying hen manure (25 % solids)	10.0	2.5	1.6
Iron hydroxide	0.2	0.2	
Natural zeolite	1.0	1.0	
Water (60 ^{o}C)	16.2		
Total	28.6	3.7	1.6

The mixture from the mixing tank is pumped by a Bredel SPX (Netherlands) 100 mm peristaltic pump into the digester tank.

Digester

Designs with squat tanks (H/D eq. .25) have horizontal mixers with submersible electric motors. These mixers can be positioned by a rope and pulley combination. Repairing of these mixers requires the emptying of the digester. The rope/pulley combination is prone to failure. The designs have also diaphragm roofs that can be used as gas storage. These diaphragm roofs develop leaks and need to be replaced regularly.

Fischer et al. (2005) comment in a paper on the use of squat digesters with horizontal mixers and H/D equal to .25 and digesters with H/D equal to one and vertical mixers. The tall digesters with preheated substrate produce the same amount of gas with a retention time of 20 days as the squat digesters with the substrate loaded at ambient temperature with a retention time of 40 days.

For this design a fused glass steel digester with a H/D ratio of one, a vertical mixer and a hard top is chosen. The digester tank has a diameter of 12 m and a height of 12 m (1 300 m3). It is erected on a steel reinforced concrete sole. The tank is thermally insulated. At the bottom there are two manholes with sufficient size. One for human access, the other for pipes should it be necessary to remove grit and sand. In the roof a opening can be made of sufficient size to remove the mixer. The size has to be determined together with Stamo.

The digester tank is mixed with a Stamo (Sweden) top mounted mixer. The mixer has sufficient capacity to keep the grit (CaCO3 and others) in suspension.

The digester effluent flows by gravity in an insulated post digester with a diameter of 12 m and a height of 12 m (1 300 m3). This digester is of fused glass steel with the same sole as the main digester. This digester is mixed with a Stamo top mounted mixer. The post digester will generate 15 % extra biogas (Angelidaki et al. 2005). A larger gas yield can be expected as the digester will function as an inhibited digester. There is however no data available for hen manure. The post digester functions also as a buffer with more than ten days storage. The content of the post digester can also be used as inoculum should there be a need to empty the main digester.

Start-up of the digester

One option is to import a few hundred tons of digestate from an operating biogas plant using hen manure as substrate. Substrate can then be added until the digester is full and normal operation can be started.

The biogas plant in Langenwetzendorf Germany (Dinkloh 2004) uses hen and swine manure and maize silage as substrate. It had a long adaptation period from 2006 onwards and operates with a total nitrogen concentration of 9 - 11 g/l. The effluent of this digester is well suited as inoculum for a hen only manure digester.

During start-up of the digester each day about 3 % of the liquid volume in the digester is added with a mixture of 10 % TS of hen manure, 4 % TS of natural zeolite and 86 % water, until the digester is full. After that the loading rate is slowly increased to 10 % digester volume per day.

During start up the biological health of the digester should be monitored. Safley et al. (1985) used the ratio of bicarbonate alkalinity to total alkalinity and the fraction of carbon dioxide in the biogas..

An alternative is the start up of the digester with sludge from waste water clean up. The digester is first filled with sludge and zeolite to a total solids concentration of 14 %. This mixture is then replaced by the normal substrate mixture following the procedure as outlined above. It will take a long time until the microbe population is adapted to the high total ammonium concentration of the hen manure.

Effluent treatment

The effluent is pumped by a Bredel SPX (Netherlands) 100 mm peristaltic pump from the digester tank to a FAN-Bauer (Germany) screw-press PSS 3.2 and is separated into a thick and thin fraction. The thick fraction is loaded by conveyor belt on a dump truck and brought in part to the existing composting/drying facility. There it is picked up and packed by independent contractors.

About 40 m^3/day can be evaporated using the waste heat of the generator, with a two stage evaporator. The liquid is first acidified and send to a settling pond and from there to an evaporator. Costs are 10 €/m3. Investment is 800 000 € (Doehler et al. 2012). Costs per m^3 can be halved by using single pass evaporation. Irrigation water in Jordan is priced at 0.5 €/m^3 in the area north of Amman (Cooper 2011) and recycling of the water is not economical.

The thin fraction can be used as an organic liquid fertilizer. A combination of irrigation water and fertilizer is used in Jordan (Rusan et al. 2002). The the organic fraction is removed in a zeolite bed. The cleared water contains 5 - 7 kg/m^3 of nitrogen.

Further absorption on zeolite can be done. Al-Dwairi et al. (2013) measured N_{tot} uptake for two different natural zeolites in Jordan of 0.012 kg/kg and 0.016 kg/kg using clarified city waste water. Loading rate can be increased to 0.05 kg/kg of ammonia on zeolite at the 5 kg/m3 nitrogen concentration of the effluent of the digester (Kucic et al. 2012). The costs for the zeolite can be off-set by selling the loaded material as soil improver and substitute for urea.

The use of natural zeolite in horticulture and agriculture reduces the need for fertilizer and irrigation water (Maria-Ramirez et al. 2011) and Al-Qurallah et al. (2013). In Jordan studies have been done by Ibrahim et al. (2001), Mohammad et al. (2004) and Al-Qurallah et al. (2013) on the use of zeolite as soil improver. In 2011 275 ton (20 €/ton) of zeolitic tuffs were used in Jordan itself for agricultural purposes (Zurqeih 2012). Local zeolite use was in 2009 2 500 ton. A market analysis has to be performed.

The cheapest option (with no re-use of the water) is to acidify the liquid fraction and lead it to an evaporation pond. Smell and evaporation of ammonia should be minimal due to the low pH. Evaporation rates are 2 - 5 m/a. The required area is about 20 000 m^2.

Generator

The biogas is piped to an evaporative cooler, droplet separator and heater and from there to the engines or to a Bredel (Netherlands) peristaltic pump should the gas be used at a different site.

There is a flare (Van der Wiel, Netherlands) in case the engine does not operate.

There are flares (Van der Wiel, Netherlands) in case the engines do not operate or the gas is not required.

The electricity production is 550 kWe and the required electric capacity is 800 kWe to have the engine run at its optimal range (70 %) with regard to thermal efficiency and wear.

Proposed is a used Jenbacher generator. New they are (800 kW) 800 000 €.

Gas storage

Gas storage for electricity production requires extra investment with no added value. Fluctuations in the gas production are best taken care with more or less electricity production. The excess gas can be flared, when the gas engine is inoperable.

- Diaphragm storage (Sattler Switserland) Most German plants have diaphragm storage instead of a roof and a number of Chinese plants have diaphragm storage independent of the digester. The Ruseifah gas storage membrane has failed and is not being repaired.
- Water tank equalization. A concrete tank can be build where water is pumped out or in depending on the gas storage required. This option is adopted in many family size biogas plants.

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